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Magnetic force microscopy of Fe nanoparticles buried into SiO_2

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Abstract. The MFM-images of the array of separately placed α-Fe nanoparticles buried into SiO_2 formed by ion bombardment have been obtained for the first time. The method of the computer analysis of MFM-images with consideration of the shape and magnetic properties of MFM-tip apex has been developed and applied for analyzing of the obtained magnetic images.

Introduction

Nanostructured surface magnetic materials have been being objects of close interest for investigating for several last years due to the perspective of creation of quantized magnetic disks based on such media. The magnetic force microscopy is a powerful instrument to study for such objects due to its high potential possibilities in investigating of magnetic properties of surface structures with nanometer resolution. However the images obtained with magnetic force microscope (MFM) consist of the complicated convolution of the magnetic and shape features of the MFM tip apex with magnetic field created on tip by the sample magnetic nanostructures. That is why it is necessary to hold further analysis based on computer simulation of MFM-images to interpretate the obtained results.

In this paper there are presented for the first time the results of MFM investigations of SiO_2 stripes on silicon containing ultrafine ferromagnetic α-Fe particles formed by ion bombardment. Previously [1] we have studied for magnetic and optic properties of such samples with the following methods: FMR, Mössbauer spectroscopy, optic spectroscopy, magnetooptics, X-ray analysis and electron microscopy. In order to interpretate the obtained MFM-images, the computer method of analysis has been developed, which was firstly presented for analysis of the MFM-images of single domain Ni nanoparticles [2]. The consideration of shape and magnetic features of MFM-tip close to the real ones has been made as the improvement of the computer method of analysis mentioned above.

Experiments and discussions

In spite of good magnetic properties of Fe the formation of ferromagnetic materials based on it meets some difficulties connected to bad chemical features of Fe which is quickly oxidized in the presence of Oxygen. In this work the investigated magnetic samples based on Fe were formed in the following way. The stripes of SiO_2 formed on silicon with about 100 nm in height and 1500 nm in width (Fig. 1(a,c)) were bombarded by Fe^+ ions with energy of 40 keV and doze of 1.4×10^{17} ions/cm^2, afterwards α-Fe ferromagnetic nanoparticles with typical sizes from 60 to 80 nm and disk-like shapes with diameter-to height ratio from 1.5 to 2.5 were formed on the depth up to 60 nm (Fig. 1(b,d)).

Nanoscope IIIa scanning probe microscope working in the oscillating mode [3] has used to investigate the topography and magnetic properties of the described sample. The MFM-tips were magnetized along their axis of symmetry beforehand. Fig. 1(e) presents the MFM-image of single stripe after *ex situ* magnetizing along X direction with the external magnetic

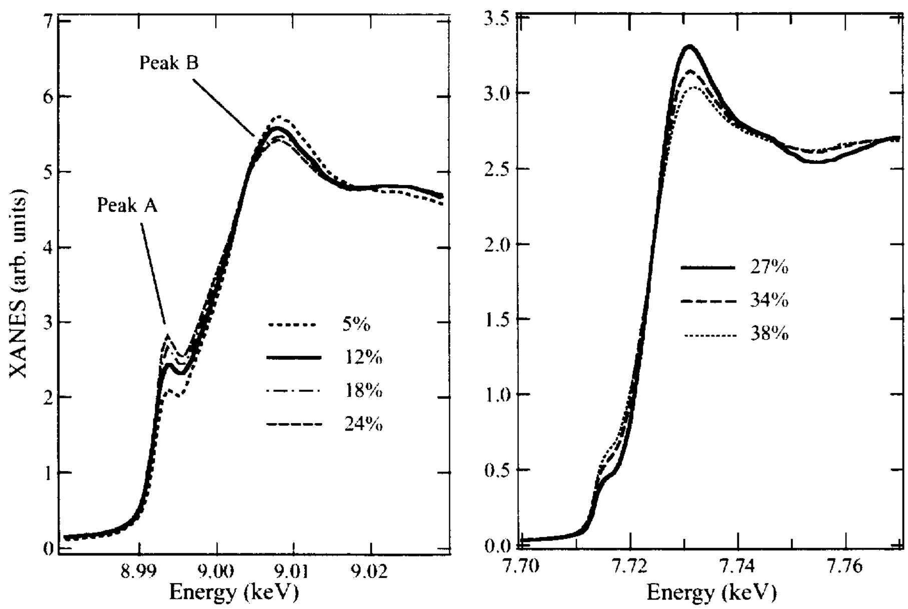

Fig. 3. Normalized XANES spectra for as-made samples containing copper (left) and cobalt (right) in different concentrations.

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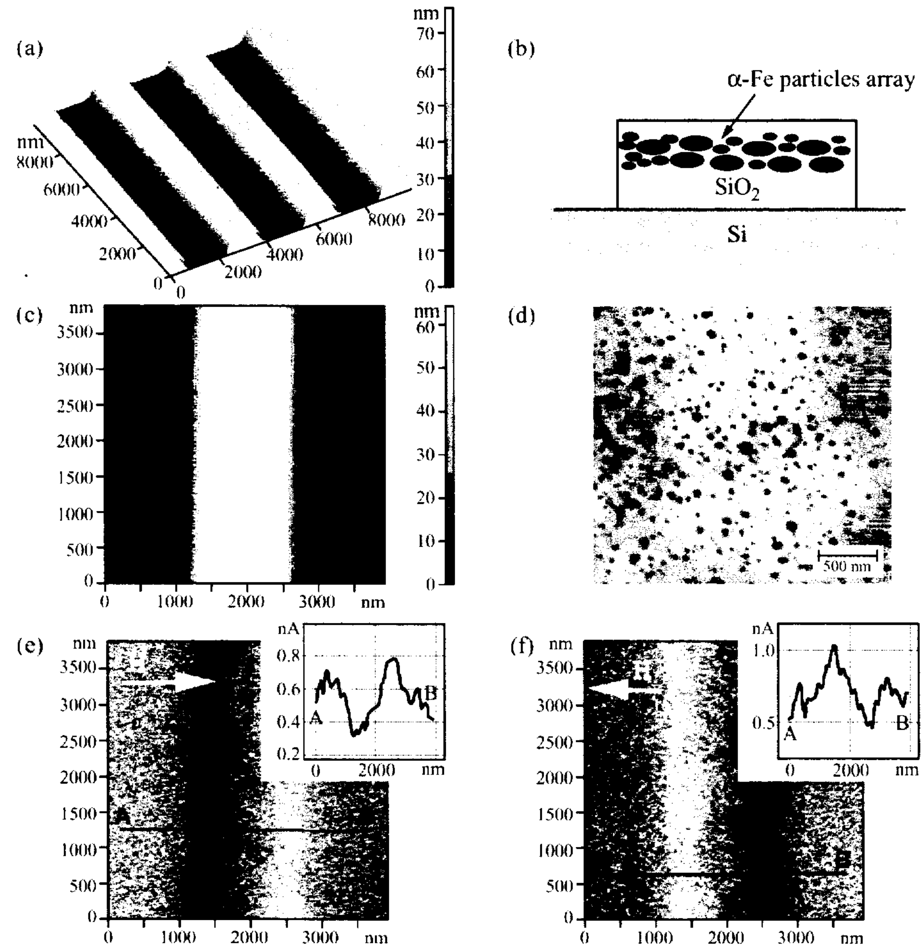

Fig. 1. The topography, structure and MFM-images of the sample with α-Fe nanoparticles formed by ion bombardment buried into SiO_2 stripes. (a) The topography of a sample surface area; (b) the structure of a stripe and (c) topography of the stripe (top view); (d) the image of α-Fe nanoparticles array into SiO_2 obtained with electron microscopy; (e), (f) the MFM-images of the stripe after *ex situ* magnetizing of the sample in the directions marked by arrows. Insets present the MFM-signal profiles along the accentuated lines.

field of about 3000 Oe. Such strong MFM-signal is a result of rather high magnetization of ferromagnetic nanoparticles and can be explained by the fact that the most of the particles are in single domain state that is confirmed by the previous investigations [1]. After applying of the magnetic field in opposite direction the MFM-signal has inverted (Fig. 1(f)), that is caused by the reverse of total magnetic moments of every Fe nanoparticle. Such MFM-signal reverse was also observed when the external magnetic field of the smaller magnitudes (up to 300 Oe) was applied, so one we can say that the magnitude of the sample coercivity is not more than 300 Oe at least, which is also in agreement with data obtained in [1].

From the obtained MFM-images of the single stripe it is clear that the signals of separate particles cannot be distinguished, moreover the profile of the MFM-signal has rather large

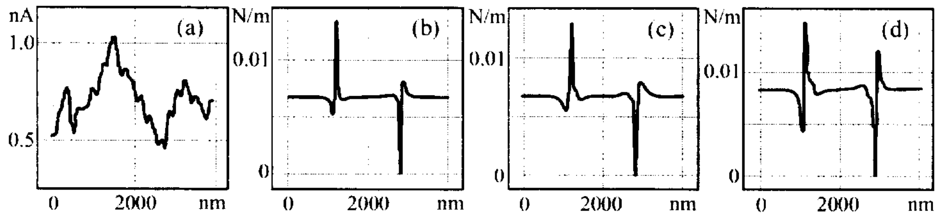

Fig. 2. The profiles of the experimental and simulated MFM-images across single SiO_2 stripe containing α-Fe nanoparticles buried into it. (a) the profile of the experimental MFM-image; (b), (c), (d) the profiles of the MFM-images simulated in the approximation of the MFM-tip apex: (b) by the point magnetic dipole, (c) by the cone covered by magnetic coating, (d) by the truncated cone covered by magnetic coating.

width. The computer program for simulation of MFM-images with taking into account the shape and magnetic features of MFM-tip apex has been developed to explain these facts.

From the theory of MFM-response [3] it is known that MFM-image presents the distribution of z-component of gradient of magnetic force of interaction between tip and sample which is determined by the equation (in case of absence of currents):

$$F_z' = \iiint\limits_{\text{tip}} \frac{\partial}{\partial z} \left[\mathbf{M}_{\text{tip}}(\mathbf{r}) \cdot \nabla\right] H_z(\mathbf{r}) dV_{\text{tip}}. \tag{1}$$

Here $\mathbf{M}_{\text{tip}}(\mathbf{r})$ — tip magnetization in $\mathbf{r}$ point, $H_z(\mathbf{r})$ — z-component of the magnetic field created by the sample on the tip in $\mathbf{r}$ point. The model of dipole-dipole interaction [2] when magnetic volumes of the tip and the sample are divided into physically small fragments of cubic shape and each fragment is replaced by the point magnetic dipole has been used. So the Eq. (1) can be rewritten by sum of interactions between the separate dipoles:

$$F_z' = \sum_{i-\text{tip}} \sum_{j-\text{sample}} \frac{\partial}{\partial z} \left[\mathbf{M}^i_{\text{tip}}(\mathbf{r}^{ij}) \cdot \nabla\right] H_z^{ij}(\mathbf{r}^{ij}). \tag{2}$$

Here the summarizing is held among i-th cubs of the tip and j-th cubs of the sample.

The held computer simulation was based on Eq. (2) with the approximation of the nanoparticles array by thin ferromagnetic film which was divided into small cubic fragments with 50 nm in size. Figure 2 presents the results of the simulation of the profiles of the MFM-images across the single stripe held in the case of that the tip height in lifting mode was 100 nm and it was uniformly magnetized along Z-axis and all of the particles were in single domain state and their total magnetic moments were ordered along X direction. Figure 2(b) presents the MFM-image profile in case of tip approximation by point magnetic dipole. It is clear that magnetic signals from the separate particles are not distinguished that correlates to experimental data (Fig. 2(a)) but there is no agreement in width of the corresponding curves of the magnetic signals. To explain the observed experimental wideness the MFM-tip has been approximated by the cone covered with magnetic coating and then by the truncated cone with magnetic coating. We can observe the consequent slight increase of wideness in both cases (Fig. 2(c, d)) but it not enough to explain the experimental results. We think that some not correspondence of simulated MFM-images to experimental results may be due to that we haven't yet considered the fact that MFM-tip can have complicated non-uniform structure of magnetization. The further additional investigations are necessary to check this affirmation.

Conclusion

Thus, in this work the MFM-images of the array of separately placed α-Fe nanoparticles buried into SiO_2 formed by ion bombardment have been obtained for the first time. The method of the computer analysis of MFM-images with consideration of the shape and magnetic properties of MFM-tip apex has been developed and improved. It has been applied to analyze the obtained magnetic images. Some not correspondence of the results of the computer simulation to the experimental data may be explained by necessity of the further consideration of internal nonuniform magnetization structure of the MFM-tip.

Acknowledgements

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